

Mass ratio determination from H_α lines in Black-Hole X-ray transients

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ABSTRACT

We find that the mass ratio q in quiescent black hole (BH) X-ray transients is tightly correlated with the ratio of the double peak separation (DP) to the full-width-half maximum ($FWHM$) of the H_α emission line, $\log q = -6.88 - 23.2 \log(DP/FWHM)$. The correlation is explained through the efficient truncation of the outer disc radius by the 3:1 resonance with the companion star. This is the dominant tidal interaction for extreme mass ratios $q = M_2/M_1 \lesssim 0.25$, the realm of BH (and some neutron star) X-ray transients. Mass ratios can thus be estimated with a typical uncertainty of $\approx 32\%$, provided that the H_α profile used to measure $DP/FWHM$ is an orbital phase average. We apply the $DP/FWHM - q$ relation to the three faint BH transients XTE J1650-500, XTE J1859+226 and Swift J1357-0933 and predict $q = 0.026^{+0.038}_{-0.007}$, $0.049^{+0.023}_{-0.012}$ and $0.040^{+0.003}_{-0.005}$, respectively. This new relation, together with the $FWHM - K_2$ correlation presented in Paper I (Casares 2015) allows the extraction of fundamental parameters from very faint targets and, therefore, the extension of dynamical BH studies to much deeper limits than was previously possible. As an example, we combine our mass ratio determination for Swift J1357-0933 with previous results to yield a BH mass of $12.4 \pm 3.6 M_\odot$. This confirms Swift J1357-0933 as one of the most massive BH low-mass X-ray binaries in the Galaxy.

Subject headings: accretion, accretion disks - binaries: close - Stars: black holes, neutron stars, dwarf novae, cataclysmic variables - X-rays: stars

1. Introduction

Stellar-mass black holes (BHs) are mostly detected through dramatic X-ray outbursts exhibited by transient X-ray binaries (SXTs; Tanaka & Shibazaki 1996). About 60 BH candidates have been identified in the 50 year lifetime of X-ray astronomy (Corral-Santana et al. 2015), although only 17 of these have been confirmed by dynamical studies i.e. they possess a mass function $f(M) = M_1 \sin^3 i / (1+q)^2$ in excess of $3 M_\odot$, where $q = M_2/M_1$ is the mass ratio of the companion star to the compact object. The reason for the low rate of confirmed BHs lies in the difficulty of detecting the companion star for quiescent optical magnitudes fainter than ~ 22 . Time-resolved spectroscopy with signal-to-noise ratio $S/N \gtrsim 10$ is

typically needed to detect the weak absorption features and trace their orbital motion. Determining the binary mass ratio is even more challenging as it also requires resolving powers $R \gtrsim 5000$ to measure the rotational broadening of the absorption lines (e.g. Casares & Charles 1994). In addition, moderately short integration times are essential to avoid significant orbital smearing. It should be mentioned that alternative methods based on the radial velocities of the disc emission lines are uncertain and prone to large systematic effects (see e.g. Marsh et al. 1994). A critical review on the determination of system parameters in BH SXTs can be found in Casares & Jonker (2014).

In Casares (2015) (henceforth Paper I) we showed that the full-width-half maximum ($FWHM$) of the disc H_α line in quiescent BH SXTs scales

with the velocity semi-amplitude of the companion star. We here present the discovery of another correlation between q and the ratio of the double peak separation to the line width. Both relations open the door to constrain fundamental parameters and perform dynamical studies in much fainter samples of quiescent BH candidates than is currently possible.

2. Database

We have selected a sample of quiescent spectra of nine dynamical BH and two neutron star (NS) SXTs from Paper I, all with reliable mass ratio determinations. Only mass ratios obtained by resolving the rotational broadening of the companion star (the $V \sin i$ technique) have been considered. Table 1 presents our sample and the associated references. Full observational details for every target are given in Paper I. For the case of XTE J1118+480, we decided to include also 34 additional spectra obtained with the 10.4m Gran Telescopio Canarias (GTC) and reported in González Hernández et al. (2014). Note that GRO J0422+320 is not included despite having a q determination through the $V \sin i$ technique. This is because the resolution of the only three quiescent spectra available to us is too poor ($\Delta\lambda > 25\%$ of the double peak separation) for a realistic determination of the double peak separation.

For comparison we have also chosen a subsample of quiescent Cataclysmic Variables (CVs) from Paper I. From the 24 possible CVs with reliable q determinations, 13 have been rejected because the line core is dominated by a strong S-wave component which prevents us from measuring the double peak separation with the simple model outlined below. In any case, these are all CVs with large mass ratios $q \gtrsim 0.6$ which, as we will show later, are not relevant to our analysis. From the remaining 11 CVs, three have q values based on the $V \sin i$ technique (GK Per, IP Peg and CTCV J1300-3052) and another two on a direct determination of the radial velocity curves of both the white dwarf and the donor star (U Gem and WZ Sge). In the remaining six the companion star is not directly observed but robust q values are available through modeling the eclipse of the white dwarf and the hot spot (see e.g. Littlefair et al. 2008). Our CV sample is listed in Table 2.

3. The $DP/FWHM - q$ relation

Double peak separations (DP) were obtained by fitting a symmetric 2-Gaussian model to the average H_α profile in every SXT and CV. In the case of eclipsing CVs we excluded those spectra obtained within ± 0.05 phases from the time of the central eclipse. The fitted model consists of a constant plus two Gaussians of identical width and height. The continuum rectified spectra were fitted in a window of $\pm 10000 \text{ km s}^{-1}$, centered on the H_α line after masking the neighboring HeI line at $\lambda 6678$. Prior to the fit, the 2-Gaussian model was degraded to the resolution of the data by convolution with the instrumental profile¹. We adopted $1-\sigma$ formal errors on the fitted parameter as derived through χ^2 minimization. Fig. 1 displays some fit examples using our 2-Gaussian model. In addition, $FWHM$ values were extracted from single Gaussian fits to the same average H_α profiles following Paper I.

Tables 1 and 2 list the parameter $DP/FWHM$ and its propagated $1-\sigma$ error as derived from our Gaussian model fits. The evolution of $DP/FWHM$ with q is presented in Fig. 2. The figure shows that $DP/FWHM$ varies very rapidly for small q values, with a 10% increase for q under 0.2.

In order to understand this behaviour, we follow on from Paper I and start by assuming that the $FWHM$ of the H_α line is determined by gas with Keplerian velocity at a characteristic radius $R_W = \alpha R_{L1}$, with $\alpha < 1$ and R_{L1} the Roche lobe of the compact star, i.e.

$$\frac{FWHM}{2} = \left(\frac{GM_1}{R_W} \right)^{1/2} \sin i. \quad (1)$$

On the other hand, the double peak separation is set by the velocity of the outer disc, whose radius R_d is truncated by the tidal forces of the companion star (Paczynski 1977; Papaloizou & Pringle 1977). There is ample evidence for the outer disc velocities to be sub-Keplerian (e.g. North et al. 2002) and thus we decided to adopt

¹As a test we also tried fitting the model without instrument degradation and find that this only has a minor impact ($\lesssim 1\%$) on the ratio $DP/FWHM$ because both quantities are almost equally affected.

$$\frac{DP}{2} = \beta \left(\frac{GM_1}{R_d} \right)^{1/2} \sin i. \quad (2)$$

where the parameter $\beta < 1$ accounts for the fraction by which the outer disc material is sub-Keplerian. For extreme mass ratios $q \lesssim 0.25$ the disc is effectively truncated at the resonance radius of the ($j=3$, $k=2$) commensurability or 3:1 resonance radius i.e. the radius at which the disc angular velocity is three times the angular velocity of the companion star (see Hirose & Osaki 1990; Frank, King & Raine 2002). Therefore,

$$R_d \equiv R_{32} = 3^{-2/3} (1 + q)^{-1/3} a \quad (3)$$

where a the binary separation. If we now bring eq. 3 into eq. 2 and use Eggleton's relation (Eggleton 1983) to remove R_{L1}/a we find

$$\frac{DP}{FWHM} = 3^{1/3} (1 + q)^{2/3} \beta \sqrt{\alpha f(q)} \quad (4)$$

where $f(q)$ is the same expression as in eq. 6 of Paper I, i.e.

$$f(q) = \frac{0.49 (1 + q)^{-1}}{0.6 + q^{2/3} \ln (1 + q^{-1/3})}. \quad (5)$$

By computing the ratio between the double peak separation and the line width we have managed to cancel out the dependence on compact object mass and binary inclination. Interestingly, in contrast with the $FWHM - K_2$ correlation presented in Paper I, eq. 4 is very sensitive to the mass ratio for $q \lesssim 0.25$ i.e. the typical values achieved by BH SXTs.

For the sake of comparison, we also plot eq. 4 in Fig. 2 for $\alpha = 0.42$ (adopted from Paper I) and $\beta = 0.77$. Although not intended to be a fit, the alignment of the data with the model indicates that eq. 4 provides a good description of the observations. This endorses our interpretation that the strong dependence of $DP/FWHM$ with q is driven by the truncation of the outer disc radius caused by the 3:1 resonance tide. The bottom panel in Fig. 2 also displays the evolution of $DP/FWHM$ for the CV sample, with the model for $\alpha = 0.42$ and $\beta = 0.83$ superimposed. The comparison of the SXT and CV data with the

model indicates that the velocities at the outer accretion disc are sub-Keplerian by $\approx 20\%$, in good agreement with other studies (e.g. Wade & Horne 1988). Note that for $q \gtrsim 0.25$ the 3:1 resonance lies beyond $\approx 0.9 R_{L1}$ and the outer disc radius is then limited by the largest non-intersecting orbits allowed by three-body interactions (Paczynski 1977). Under these circumstances, the dependence of the outer disc radius on q is very weak (Frank, King & Raine 2002) and, therefore, a nearly constant evolution of $DP/FWHM$ versus q is expected for $q \gtrsim 0.25$.

For practical purposes, we display in Fig. 3 the variation of $DP/FWHM$ versus q in logarithmic units. A least-squares linear fit yields

$$\log q = -6.88(0.52) - 23.2(2.0) \log \left(\frac{DP}{FWHM} \right) \quad (6)$$

with a Pearson correlation coefficient $r = 0.95$. In order to estimate the error in q implied by this relation we have computed the difference with respect to the true observed values for our 11 SXTs. The distribution of differences can be approximated by a normal function with $\sigma(q) = 0.015$. This indicates that mass ratios can be realistically obtained from eq. 6 with a typical $\sim 25\%$ uncertainty.

4. Orbital effects

The spectra that we have used to produce the $DP/FWHM - q$ correlation are orbital averages. This is partly because individual spectra rarely possess enough signal-to-noise for the technique to be applicable. But also, because orbital means average out possible asymmetries in individual spectra from, for example, hot-spots or disc eccentricities which could potentially bias the determination of q .

At this point we decided to explore the impact of line asymmetries in the results of our technique. Since this can only be tested on data with sufficient signal-to-noise we have focused on the 154 high quality GTC spectra of XTE J1118+480 obtained along four different orbits over two years. We have performed Gaussian fits on every individual spectrum and computed mass ratios using eq. 6. The distribution of q values is found to peak at $q = 0.024$ (bottom panel in Fig. 4), with 68% of

the values contained between $q = 0.021$ and 0.045 . This indicates that, if q were to be obtained from a single individual spectrum, the typical uncertainty would be about $\sim 56\%$.

In order to trace the effect of line asymmetries we also extracted the V/R parameter from each spectrum, with V/R defined as the ratio of equivalent widths between the blue and the red part of the H_α profile. The two halves of the line are set from the rest wavelength till $\pm 2500 \text{ km s}^{-1}$. For example, $V/R = 0.8$ indicates a line with the red part stronger by 20% while $V/R = 1$ implies a symmetric profile. A plot of q versus V/R (see top panel in Fig. 4) seems to show a trend, with asymmetric profiles preferring slightly lower q values, although the large scatter prevents from drawing a firm conclusion.

However, as we have mentioned above, the technique outlined in this paper is most useful on phase averaged spectra because individual spectra typically have very limited signal-to-noise. Consequently, we have extracted q values by fitting Gaussians to the four orbital averages of the 154 individual spectra. The distribution of q values has a mean at 0.026 and a standard deviation of 0.005 , indicating that the typical error on phase averaged spectra is reduced to $\sim 19\%$ i.e. smaller than the 25% uncertainty drawn from the correlation. We therefore conclude that the uncertainty expected from the application of our technique to phase averaged spectra is about 32%.

5. Discussion: application to three faint BHs

In Paper I we showed that the $FWHM$ of the H_α line in quiescent SXTs and CVs is formed at $\simeq 42\%$ of R_{L1} . Furthermore, it is tightly correlated with the projected velocity of the donor star K_2 and thus, the quantity $FWHM/K_2$ can be used to extract dynamical information from single epoch low resolution ($R \gtrsim 500$) spectroscopy. In addition, we showed that $FWHM/K_2$ is weakly dependent on q , resulting in a $\sim 27\%$ flatter slope for (long-period) CVs.

We here now present a new method to estimate the binary mass ratio in quiescent BH SXTs from the properties of the H_α line. We have proved that the quantity $DP/FWHM$ is strongly dependent on q , with a 10% variation for $q \lesssim 0.25$. The rea-

son behind this is the efficient truncation of the outer disc radius by the 3:1 tidal resonance of the donor star. The correlation of $DP/FWHM$ with q , therefore, opens a new avenue to measure mass ratios in quiescent BH SXTs. The double peak separation can be solidly measured by fitting a symmetric double-Gaussian model to phase averaged H_α profiles. We estimate that instrumental resolution better than 25% of the double peak separation is required to resolve the latter. This typically demands resolving powers of only $R \gtrsim 1000$ i.e a factor ~ 5 lower than required to measure q using the $V \sin i$ technique. More significantly for observational feasibility, this method makes use of the disc H_α line which, with a typical $EW \sim 50 \text{ \AA}$, is much stronger than the weak atmospheric features of the donor star.

The relations presented in this paper and in Paper I thus allow for a reasonably accurate estimation of the system parameters in very faint SXTs which otherwise cannot be tackled with current instrumentation and standard techniques. As an example, we have applied our method to the BH SXTs XTE J1650-500, XTE J1859+226 and Swift J1357-0933. They all have $R \simeq 22-23$ and none of them has yet a mass ratio determination. We have produced averaged spectra for XTE J1650-500 and XTE J1859+226 using the data presented in Table 1 of Paper I. Regarding Swift J1357-0933 we have used a more recent and extended database reported in Mata Sánchez et al. (2015). Fig.5 displays the averaged spectra of the three BHs together with the best double-Gaussian model fits, which result in $DP/FWHM = 0.5828 \pm 0.0150$, 0.5741 ± 0.0072 and 0.5805 ± 0.0027 for XTE J1650-500, XTE J1859+226 and Swift J1357-0933 respectively. The mass ratios implied by eq. 6 are $q = 0.026^{+0.038}_{-0.007}$, $0.049^{+0.023}_{-0.012}$ and $0.040^{+0.003}_{-0.005}$, respectively. The quoted uncertainties correspond to 68% confidence regions and have been computed using a Monte Carlo simulation with 10^5 realizations. We note in passing that our mass ratio for Swift J1357-0933 is in excellent agreement with an independent estimate based on the radial velocity curve of the wings of the H_α line (Mata Sánchez et al. 2015).

Regarding Swift J1357-0933 we are now in a position to present a credible BH mass based on our scaling relations. By combining our mass ratio with the mass function obtained by means of

the $FWHM/K_2$ correlation (Mata Sánchez et al. 2015) and a conservative estimate of the inclination angle $i = 80 \pm 10^\circ$ (Corral-Santana et al. 2013; Mata Sánchez et al. 2015) we find $M_1 = 12.4 \pm 3.6 M_\odot$. This result confirms Swift J1357-0933 as one of the most massive BH low-mass X-ray binaries in the Galaxy, only rivaled by GRS 1915+105 (Reid et al. 2014).

To conclude we would like to stress that the relations presented here and in Paper I will help deepen the search for new BH transients to substantially fainter limits. They will also prove very useful in extracting fundamental parameters from large numbers of data to be delivered by new spectroscopic surveys such as GAIA or WEAVE.

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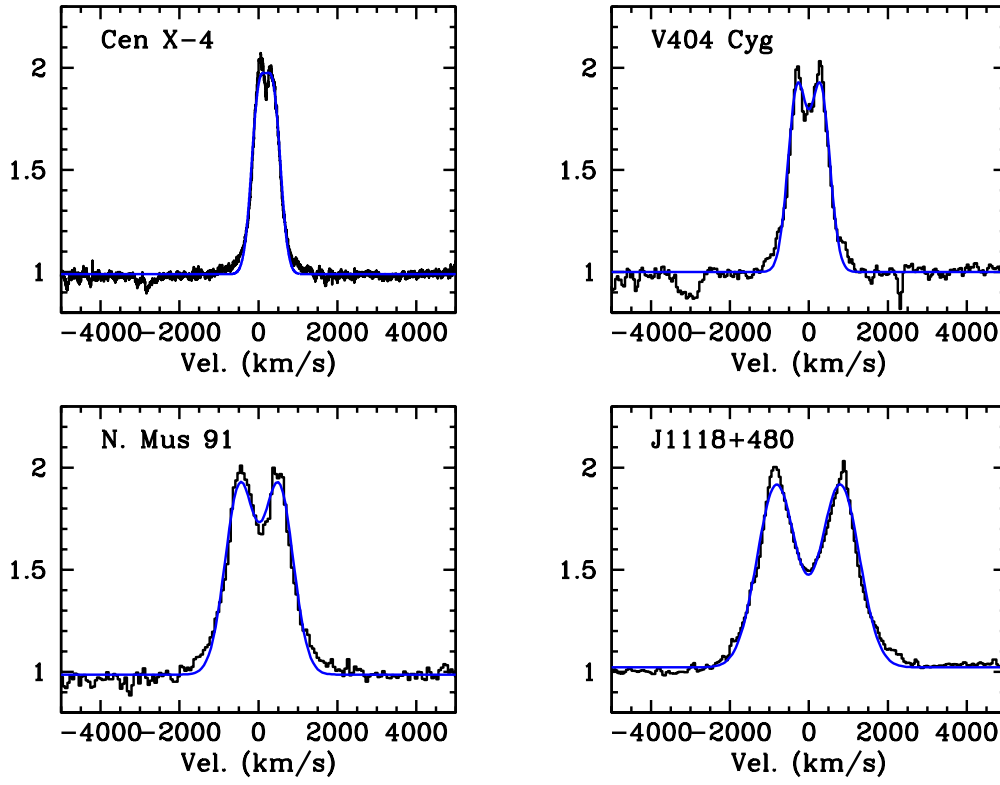


Fig. 1.— Example of double Gaussian fits to H α profiles in SXTs. A selection of average spectra, representing the entire range of $FWHM$ s, is depicted.

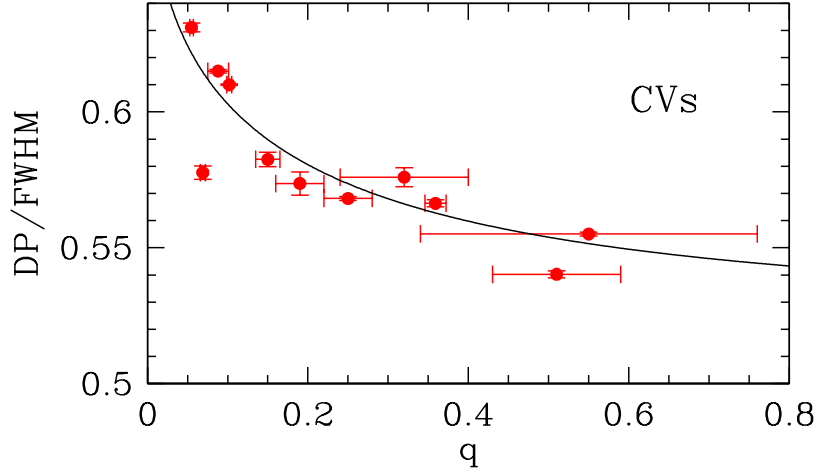
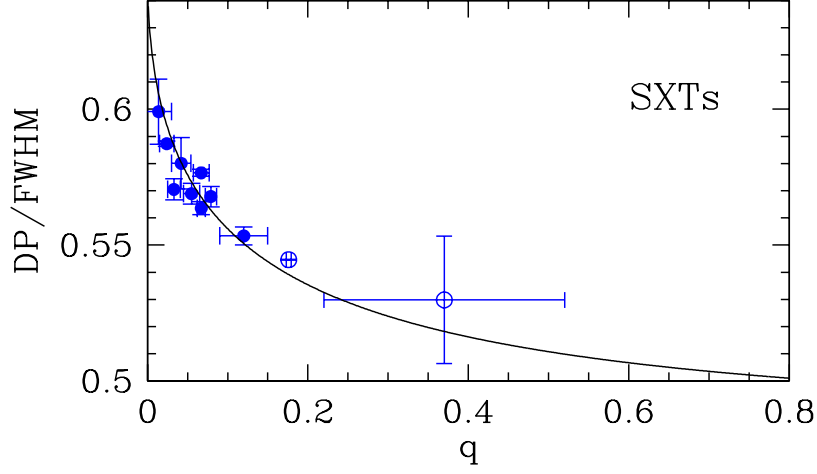


Fig. 2.— Top: evolution of the $DP/FWHM$ parameter with mass ratio q for SXTs. Blue solid circles indicate BHs while NSs are marked by open circles. The solid line represents eq. 4 for $\alpha = 0.42$ and $\beta = 0.77$. Bottom: same as above for CVs. The solid line depicts eq. 4 for $\alpha = 0.42$ and $\beta = 0.83$.

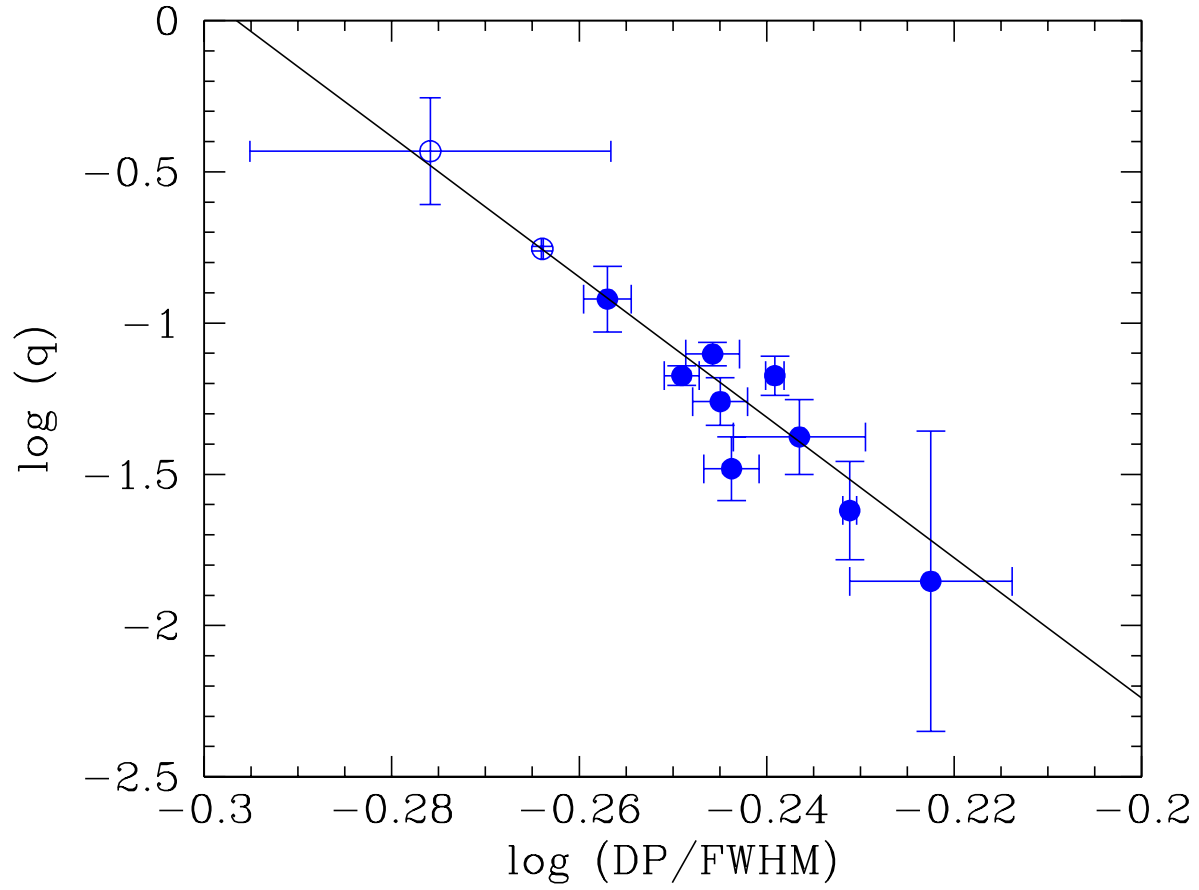


Fig. 3.— The correlation between q and the parameter $DP/FWHM$ in log units and the best linear fit.

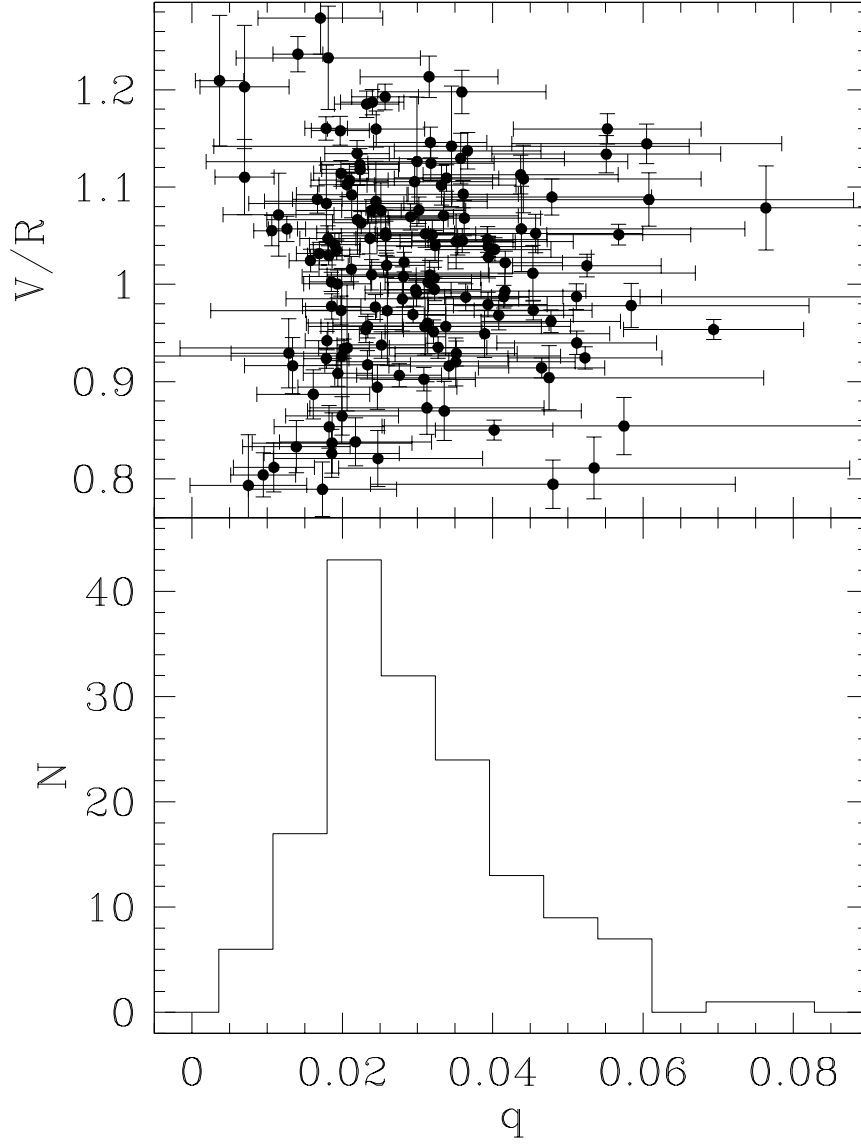


Fig. 4.— Bottom: histogram of q values derived through eq.6 from 154 GTC spectra of XTE J1118+480. Top: variation q with the V/R parameter of the $H\alpha$ profile (see text for details).

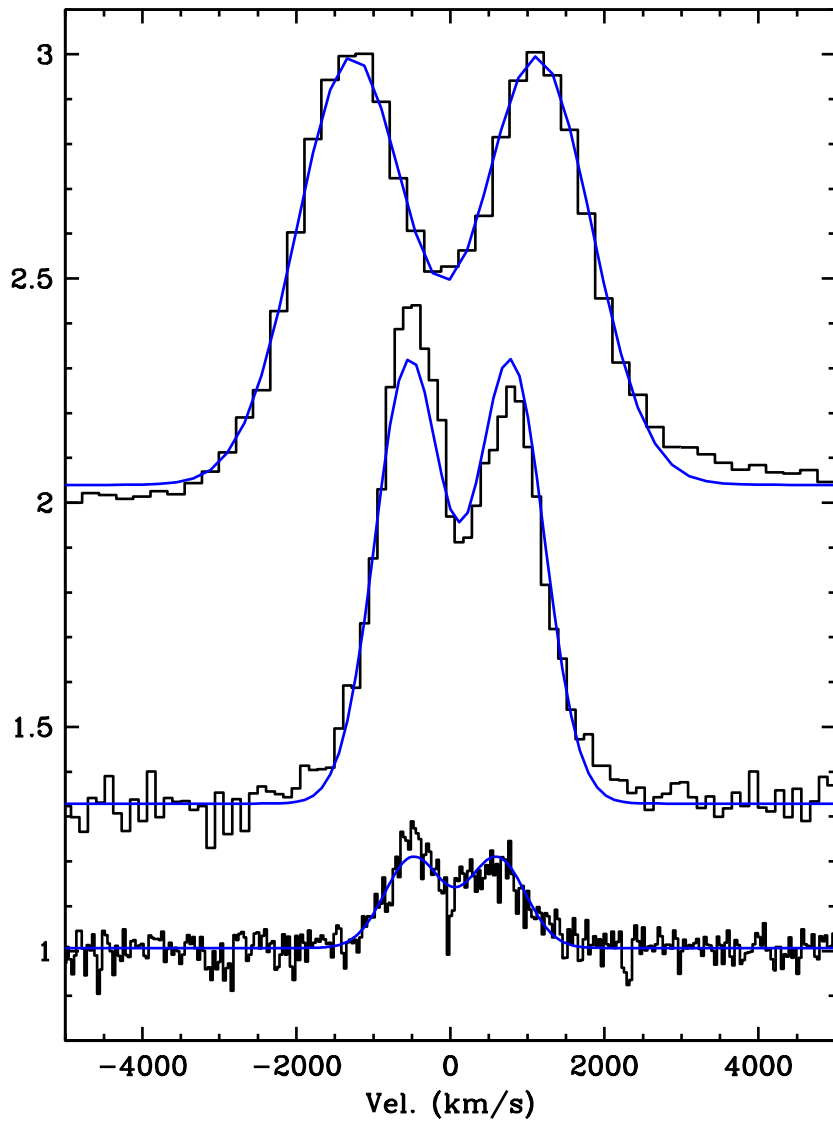


Fig. 5.— From bottom to top: average $H\alpha$ profiles of XTE J1650-500, XTE J1859+226 and Swift J1357-0933 with the best two-Gaussian model fits.

TABLE 1
DATABASE OF X-RAY TRANSIENTS

Object	q	DP/FWHM	ref
Black Holes			
V404 Cyg	0.067 ± 0.005	0.5636 ± 0.0024	1
BW Cir	0.12 ± 0.03	0.5534 ± 0.0032	2
XTE J1550 -564	0.033 ± 0.008	0.5705 ± 0.0039	3
N. Oph 77	0.014 ± 0.016	0.5991 ± 0.0119	4
N. Mus 91	0.079 ± 0.007	0.5679 ± 0.0037	5
GS 2000+25	0.042 ± 0.012	0.5801 ± 0.0094	6
A0620-00	0.067 ± 0.010	0.5766 ± 0.0013	7
N Vel 93	0.055 ± 0.010	0.5689 ± 0.0038	8
XTE J1118+480	0.024 ± 0.009	0.5873 ± 0.0010	9
Neutron Stars			
Cen X-4	0.176 ± 0.003	0.5446 ± 0.0001	10
XTE J2123-058	0.37 ± 0.15	0.5298 ± 0.0234	11

References. — (1) Casares (1996); (2) Casares et al. (2009a); (3) Orosz et al. (2011); (4) Harlaftis et al. (1997); (5) Wu et al. (2015); (6) Harlaftis et al. (1996); (7) Marsh et al. (1994); (8) Macias et al. (2011); (9) Calvelo et al. (2009); (10) Shahbaz et al. (2014); (11) Tomsick et al. (2002) .

TABLE 2
DATABASE OF CATAclysmic VARIABLES.

Object	q	DP/FWHM	ref
GK Per	0.55 ± 0.21	0.5551 ± 0.0007	1
SDSS J100658.40+233724	0.51 ± 0.08	0.5402 ± 0.0013	2
U Gem	0.359 ± 0.013	0.5663 ± 0.0013	3,4
IP Peg	0.32 ± 0.08	0.5760 ± 0.0035	5
CTCV J1300-3052	0.25 ± 0.03	0.5681 ± 0.0007	6
HT Cas	0.150 ± 0.015	0.5825 ± 0.0027	7
OY Car	0.102 ± 0.003	0.6100 ± 0.0003	8
V2051 Oph	0.19 ± 0.03	0.5737 ± 0.0043	9
SDSS 103533.02+055158.3	0.055 ± 0.002	0.6311 ± 0.0016	8
WZ Sge	0.088 ± 0.013	0.6150 ± 0.0007	10
SDSS J143317.78+101123.3	0.069 ± 0.003	0.5777 ± 0.0025	8

NOTE.— q values for GK Per, IP Peg and CTCV J1300-3052 have been obtained through the $V \sin i$ technique while those for U Gem and WZ Sge by measuring the radial velocity curves of the white dwarf and the donor star. The remaining q values are derived by modeling the eclipses of the white dwarf and the hot-spot in optical light curves.

References. — (1) Morales-Rueda et al. (2002); (2) Southworth et al. (2009); (3) Friend et al. (1990); (4) Long & Gilliland (1999); (5) Beekman et al. (2000); (6) Savoury et al. (2012); (7) Wood & Horne (1990); (8) Littlefair et al. (2008); (9) Baptista et al. (1998); (10) Steeghs et al. (2007) .